The Frozen Ocean of Snowball Earth

Stephen Warren, University of Washington

Lecture at PNNL, 2 November 2009

Recent discoveries in Earth's climate (last 30 years)

1. Meteor impacts: climatic change caused mass extinction 65 million years ago.

2. Atmospheric CO_2 oscillates with ice-age cycles.

3. "Gulf Stream" switched on and off during the last ice age.

4. Moon's gravity stabilizes tilt of Earth's axis, which keeps Earth's climate stable. The tilt stays within the range 22-25 degrees, and it is these small variations that are responsible for the ice ages. The tilt of Mars varies from 15 to 40 degrees because it lacks a large moon.

5. "Snowball Earth". Oceans apparently froze all the way to the Equator 700 million years ago.

Overview of “Snowball Earth”

(ocean freezing all the way to the equator)

observation, theory, hypothesis, puzzle, coincidence

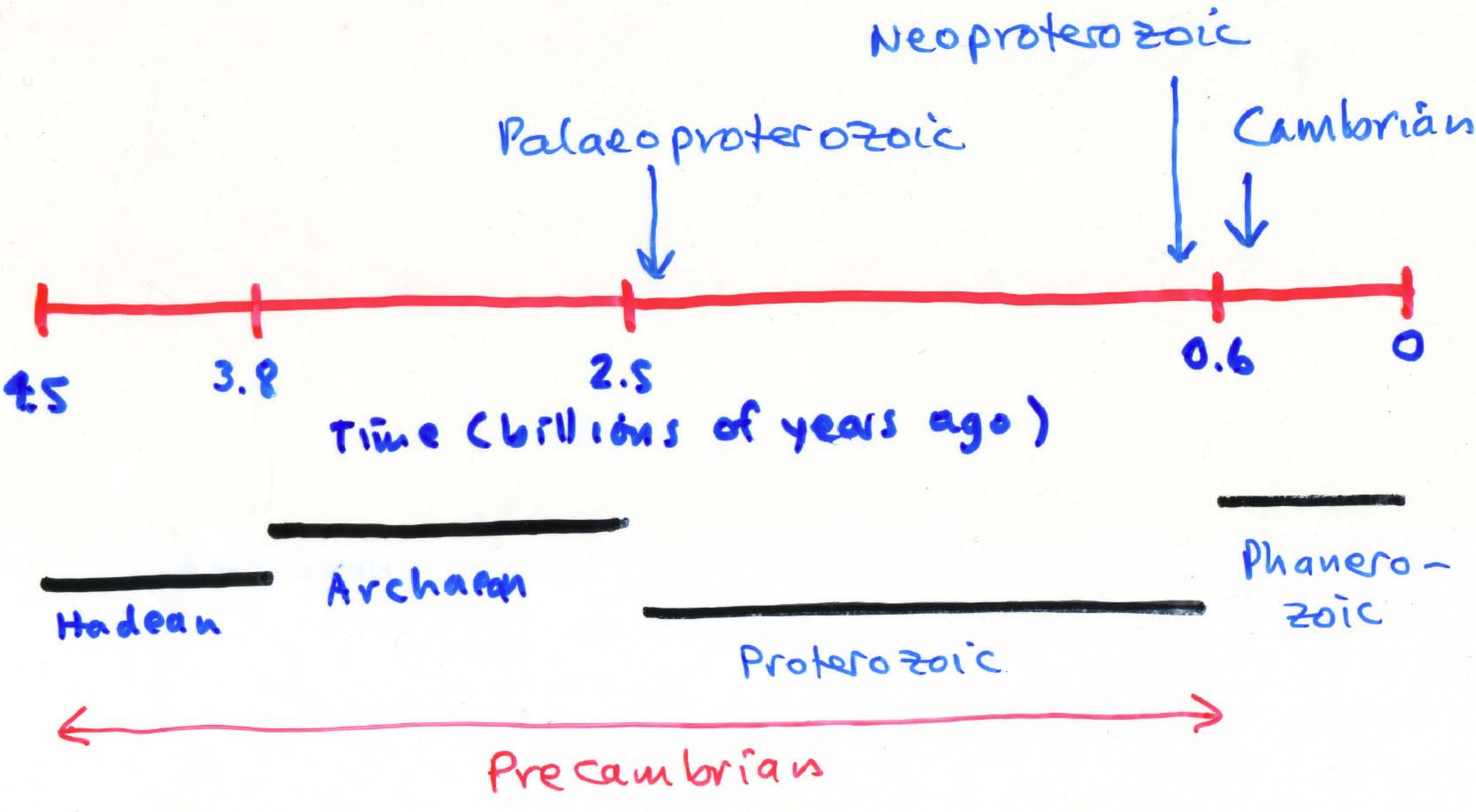
1. Observation

Glacial deposits at sea level within 10° of the paleoequator,

in the Neoproterozoic, 750-700 and 620-580 million years ago

(Harland, 1964; Evans, 2000).

Long-lasting glaciation: 7 magnetic reversals in Elatina glacial deposit in South Australia (Linda Sohl et al. 1999).


Neoproterozoic
Palaeoproterozoic
Cambrian
4.5
3.8
2.5
0.6
0
Time (billions of years ago)
Hadean
Archaean
Proterozoic
Phanerozoic
Precambrian

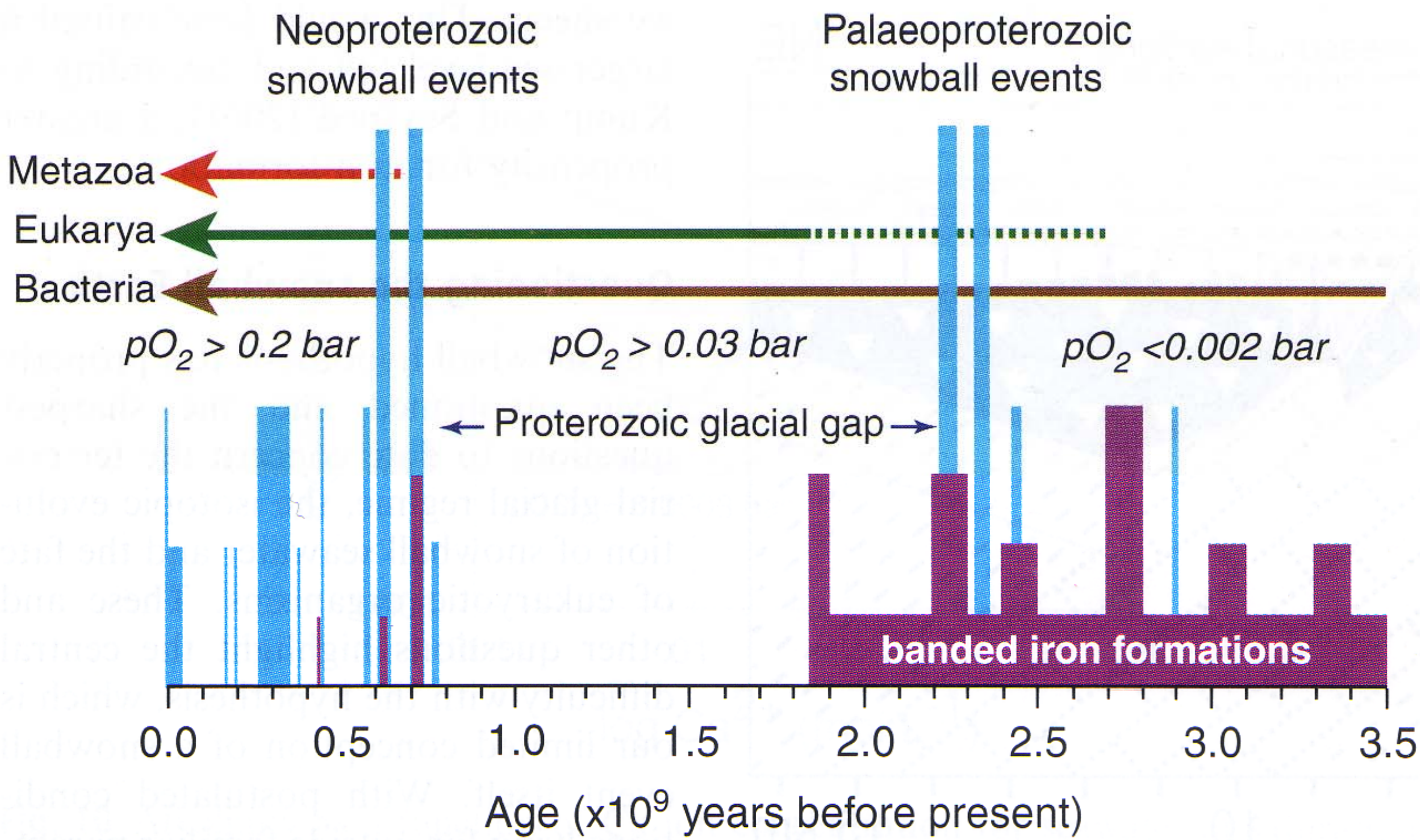
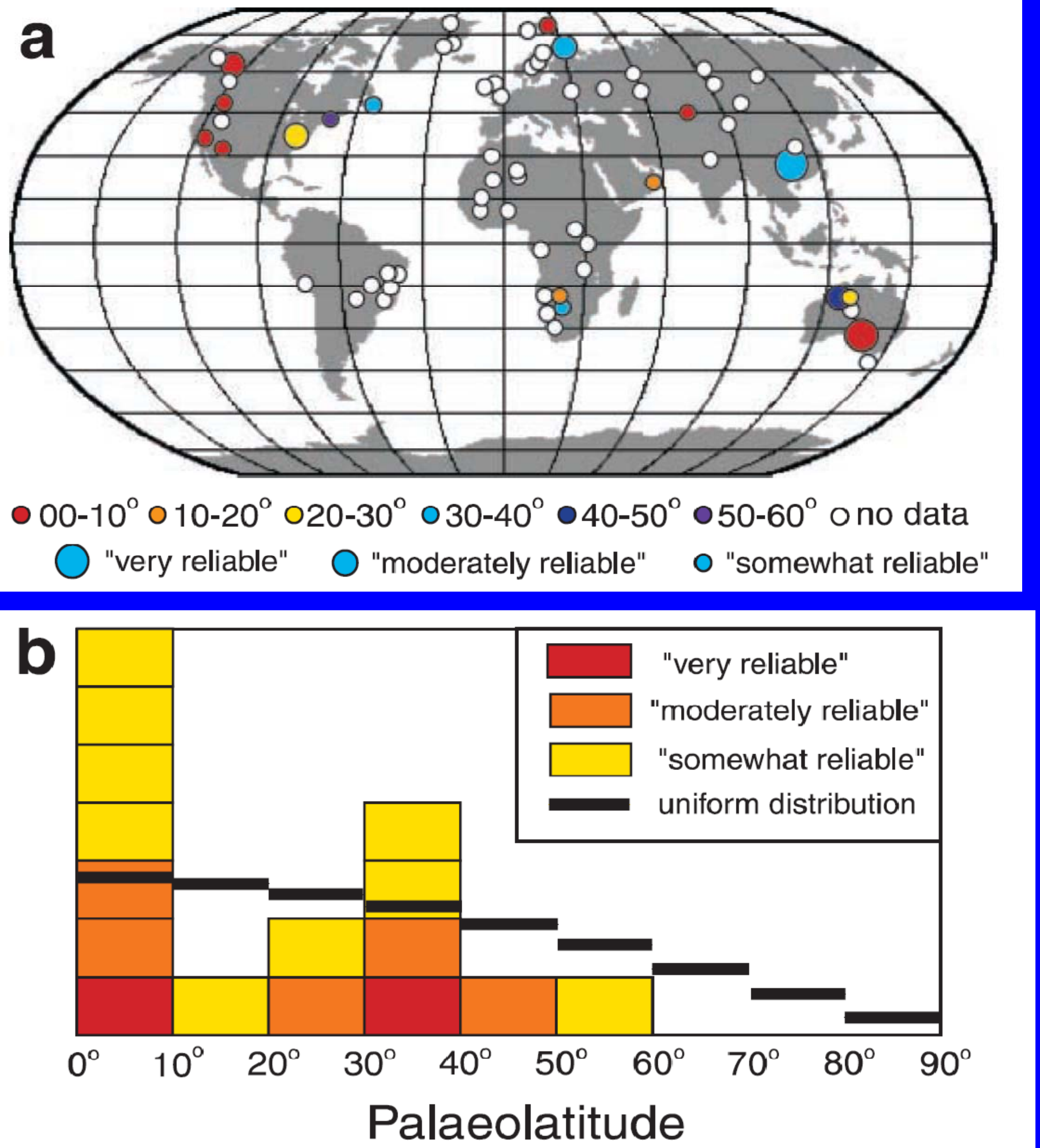


Fig. 12 Frequency of occurrence of iron formations (purple) (modified from Isley and Abbott, 1999), major glacial periods (blue) (Crowell, 1999), constraints on atmospheric oxygen levels (Rye and Holland, 1998), and steps in the history of life. Note the two eras of snowball events separated by a 1.5 billion year gap when evidence is lacking for glaciation at any latitude.



a
00-10° 10-20° 20-30° 30-40° 40-50° 50-60° no data
"very reliable" "moderately reliable" "somewhat reliable"
b
"very reliable"
"moderately reliable"
"somewhat reliable"
uniform distribution
0° 10° 20° 30° 40° 50° 60° 70° 80° 90°
Palaeolatitude

Evans (2000)

Was the ocean frozen?

1. There is geological evidence for sea-level glaciation within 10 degrees of the equator.

2. In climate models, when the greenhouse effect and/or solar energy is reduced enough to allow low-latitude land-glaciers to reach sea level, thick ice also forms over the entire ocean.

Observations explained by "Snowball Earth" hypothesis
(Hoffman et al. 1998, Hoffman & Schrag 2002)

Glacial deposits at low paleolatitudes

Thick carbonate layers capping glacial deposits, the expected consequence of buildup of atmospheric CO_2 during glaciation.

Iron deposits ("banded iron formations") after 1-billion-year absence, indicating anoxic ocean

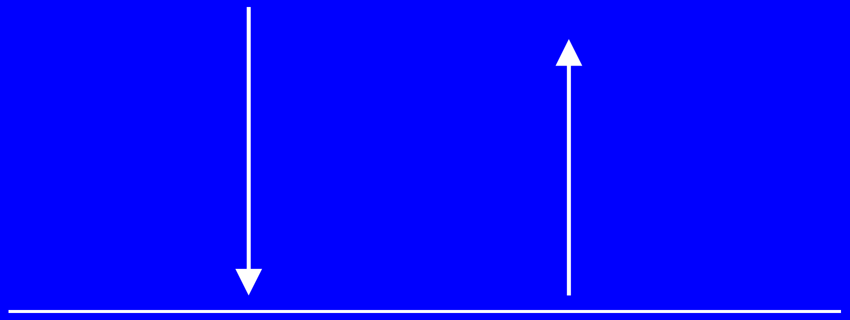
Carbon isotopes $\delta^{13}C$ = -5‰ in cap carbonates, indicating no biological fractionation

2. Theory

It's about ***albedo.***

F*down* F*up*

(incident sunlight) (reflected sunlight)



Albedo = F*up* / F*down*

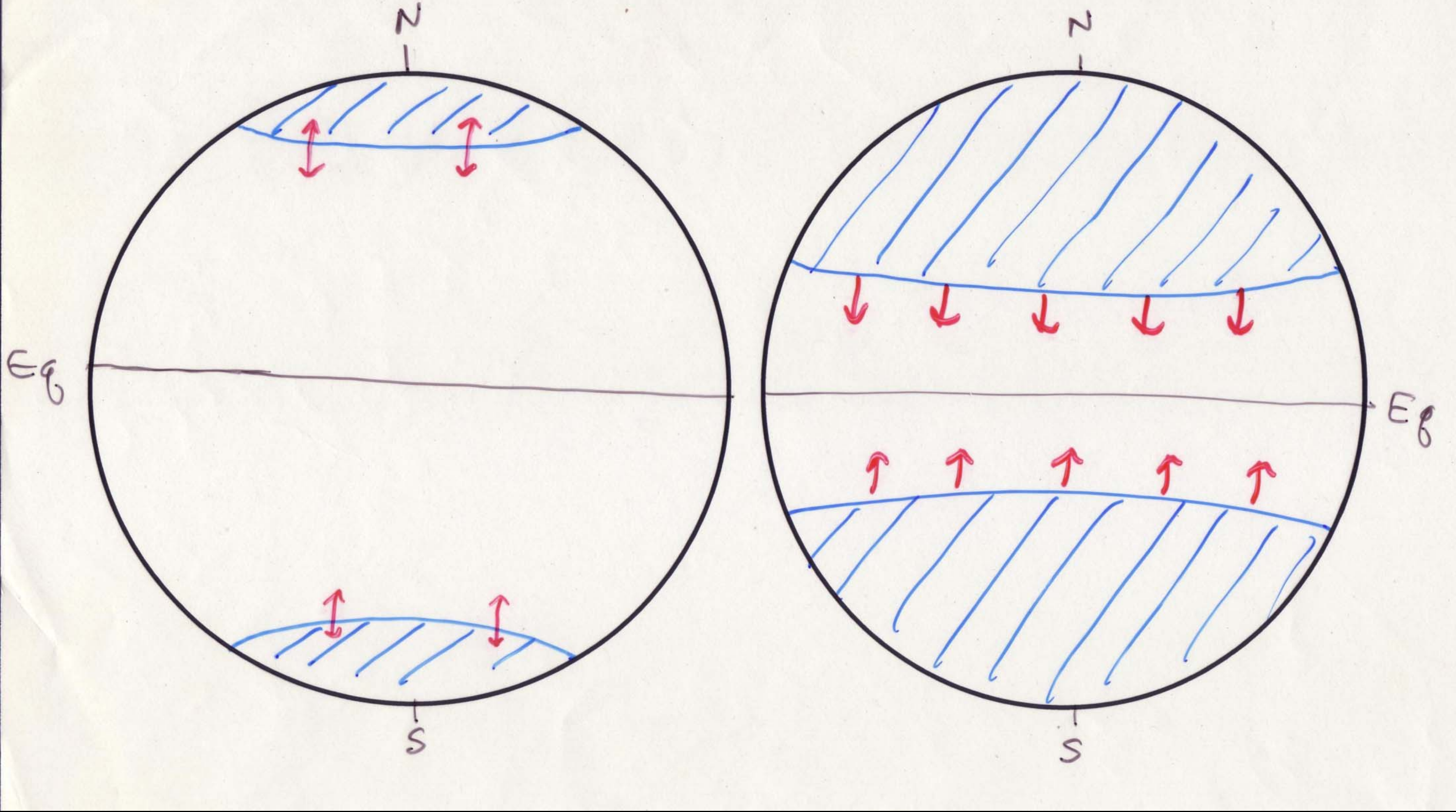
Ocean 0.07 *Snow* 0.80 *Planet* 0.30

2. Theory

Positive (amplifying) feedback of snow albedo results in an instability in many climate models.

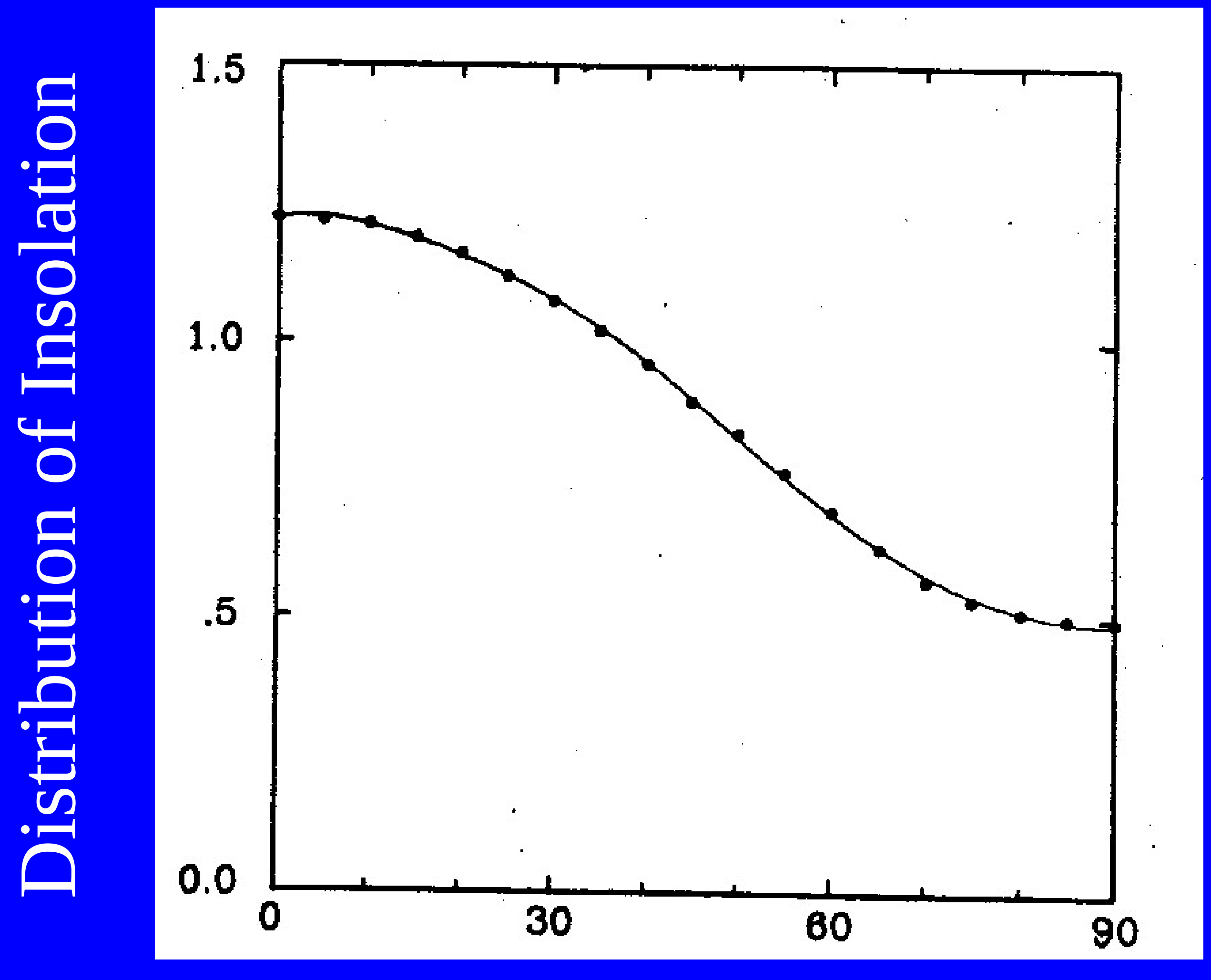
(Budyko, 1969; Manabe 1975; . . .)

	Albedo (percent) *(reflectance for solar radiation)*
Dry snow	80
Bare glacier ice	60
Bare cold thick sea ice	50
Ocean water	7

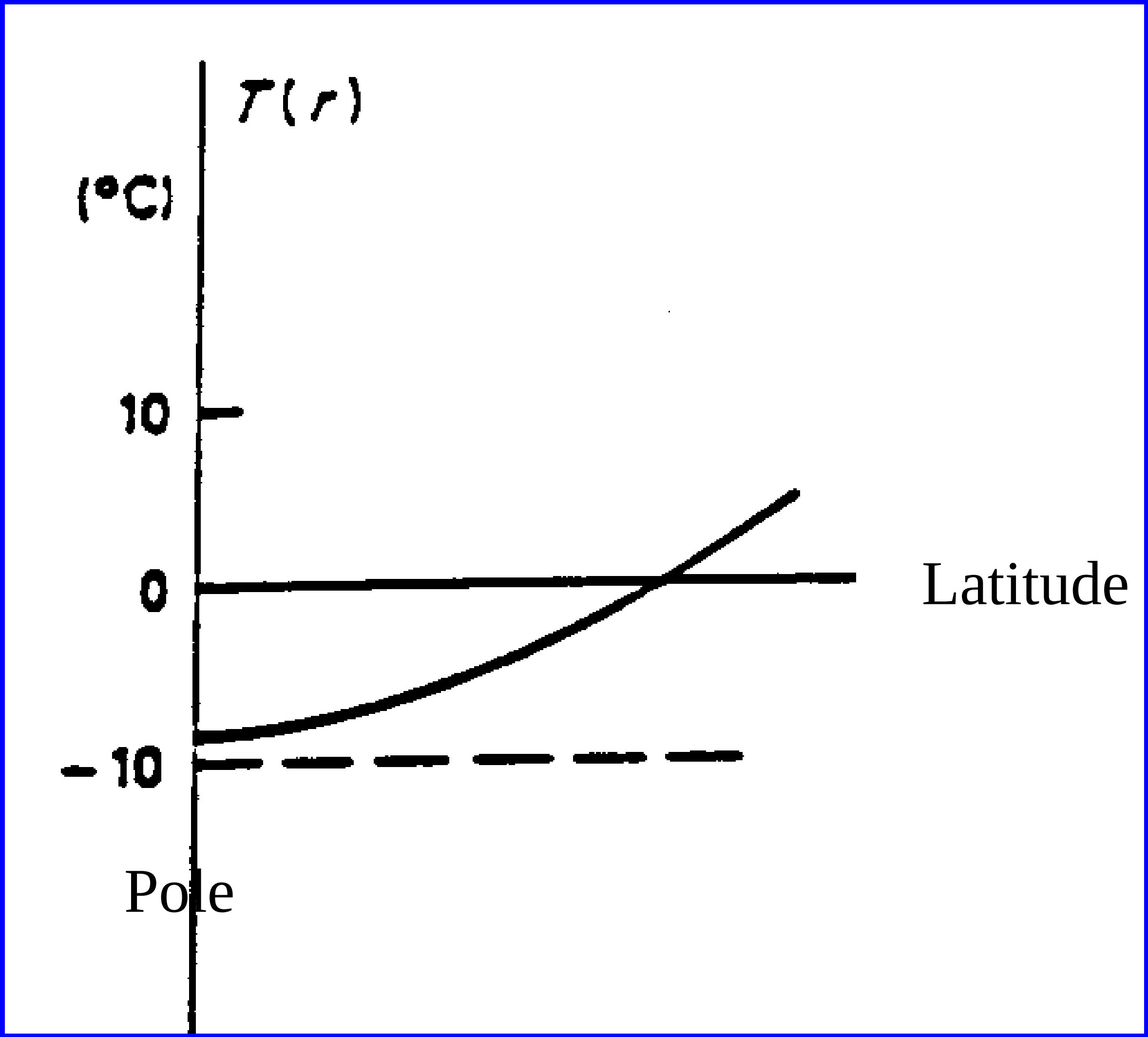


A high-albedo (snow-covered) planet
is an alternative stable state for the Earth.

Latitudinal distribution of solar radiation (annual)

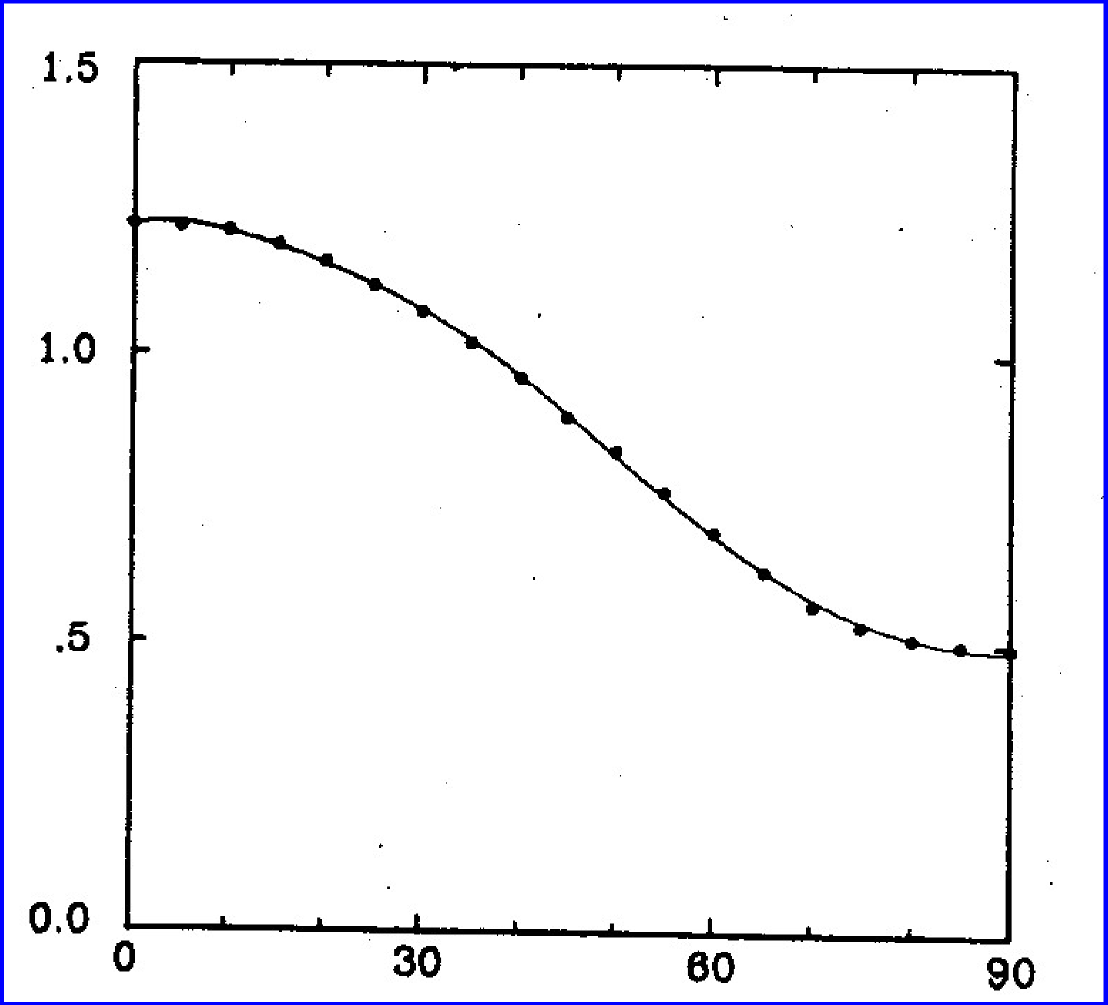


North (1984, 1991)



Schematic explanation for the small ice cap instability.

Latitudinal distribution of solar radiation (annual)



Distribution of Insolation

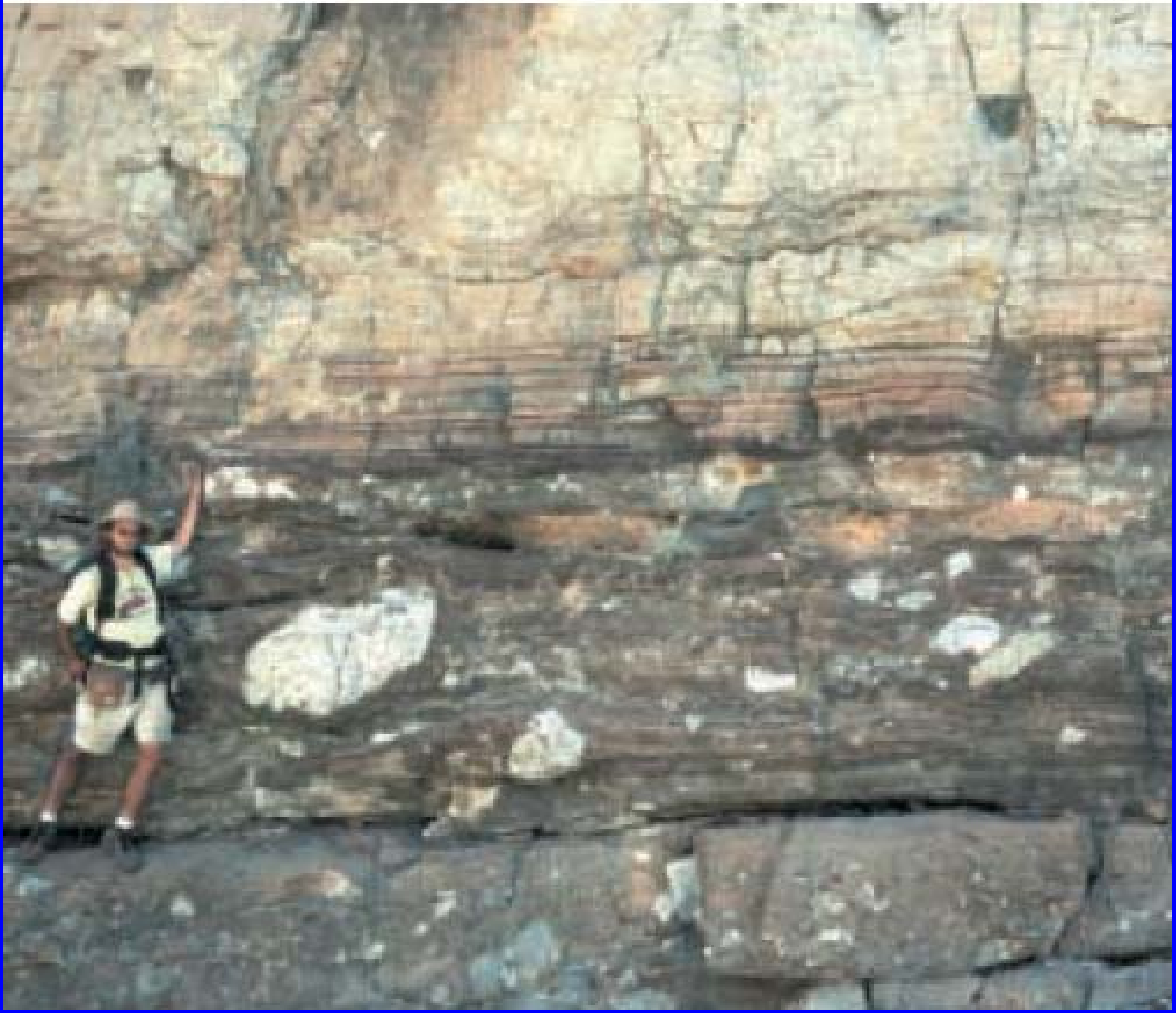
Latitude

3. Hypothesis

This “runaway albedo feedback” catastrophe actually occurred during the Neoproterozoic.

Each event lasted about 10 million years, and was ended by the greenhouse effect due to buildup of atmospheric CO_2 from volcanoes
(Kirschvink 1992; Hoffman & Schrag 1998).

[On the Snowball planet, there was no rain, no way to remove CO_2 from the atmosphere.]



Hoffman & Schrag 2002

Environmental conditions
just before transition to Snowball Earth

Sun 6% dimmer than today.
Continents small and near equator
Lots of shallow-sea continental shelf near Equator.

Cause of Snowball onset

Probably atmospheric CO_2 dropped from 1000 to 100 ppm, perhaps because methane had taken over CO_2's role in maintaining the greenhouse; then if methane production slowed CO_2 would not be able to rise fast enough to compensate.

4. Puzzle

Some surface life continued through these episodes.

Photosynthetic eukaryotic algae require both liquid water and sunlight.

Maybe the only refugia were isolated hot-spots like Hawaii, Iceland (allows for evolution of diversity)

5. Coincidence (noted by Harland 1964, and by Hoffman & Schrag 2000)

Shortly after the final Snowball event:

the “Cambrian Explosion” 575-525 Ma.

Numerous animal phyla first appear as fossils.

Was Snowball Earth responsible for the evolution of animals?

Ice ages of the Pleistocene (last 2 million years): Ice sheets covered large parts of North America, Scandinavia, and Siberia. The North American ice sheet that covered Canada 20,000 years ago was about the same size as the modern Antarctic Ice Sheet.

Snowball Earth was qualitatively different from the Pleistocene ice ages: most of the action was in the ocean!

Ocean Surfaces on Snowball Earth

(snow, sea ice, glacier ice, salt, dust)

Ocean Surfaces on Snowball Earth

(snow, sea ice, glacier ice, salt, dust)

Motivation for this research:

What kinds of refugia were available for surface life?

Glaciological terms

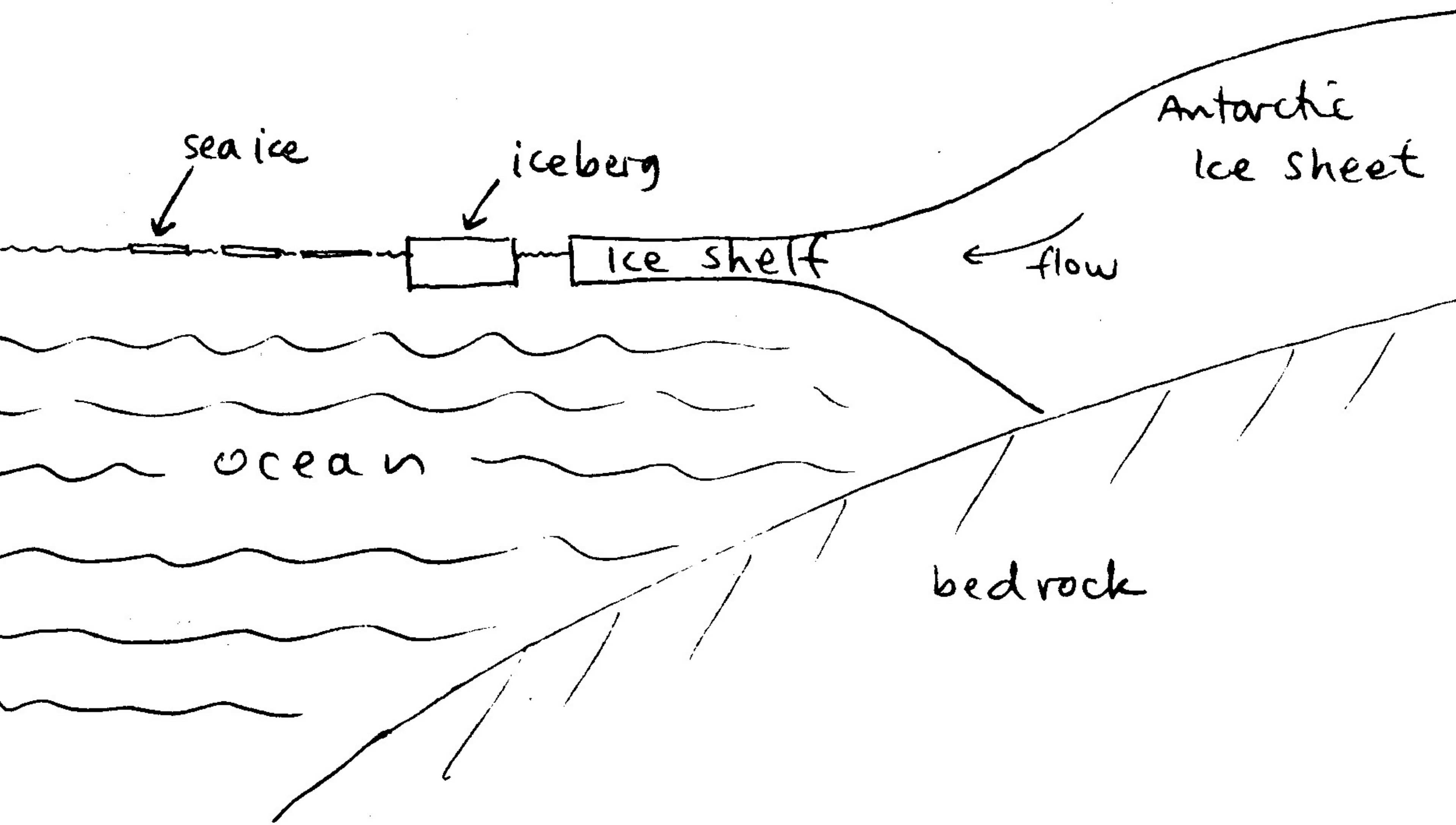
Ice sheet: Continental-scale glaciation on land

Ice shelf: Floating glacier-ice that has flowed off the continent, continuous with ice sheet

Iceberg: Chunk of ice broken off the front of an ice shelf (h~400 m)

Sea ice: Formed by freezing of seawater at ocean surface (h~1 m). Contains brine-inclusions and bubbles.

. . .



sea ice
iceberg
Antarctic
Ice Sheet
Ice shelf
flow
ocean
bedrock

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***Marine ice:* Seawater frozen to the base of an ice shelf (can be seen in capsized icebergs). No bubbles; little brine.**

Sea-glacier: (on Snowball Earth) Self-sustaining ice shelf not dependent on continental glaciation

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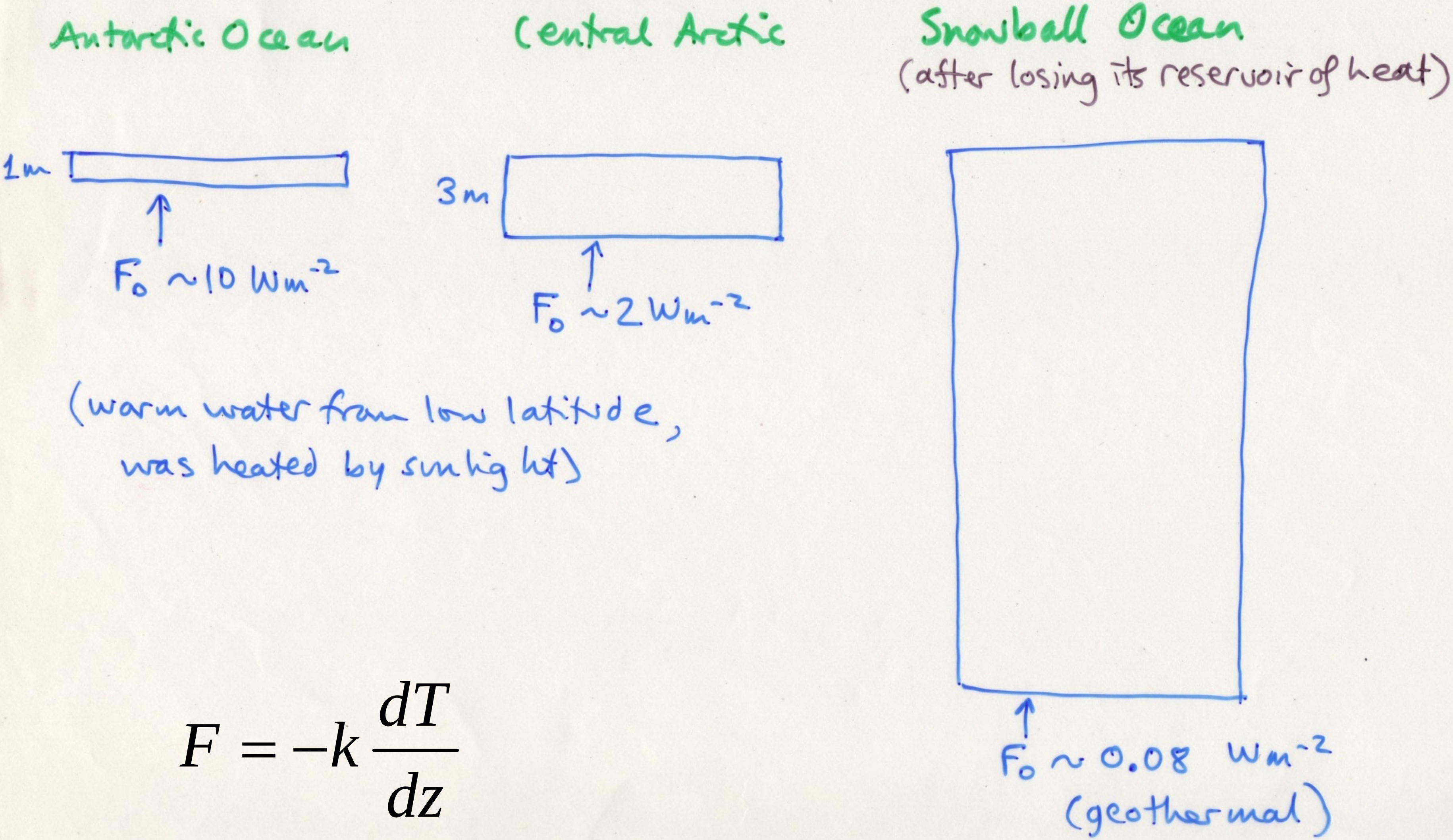
Thin ice is common on today's ocean; why not on Snowball Earth?



$$F = -k\frac{dT}{dz}$$

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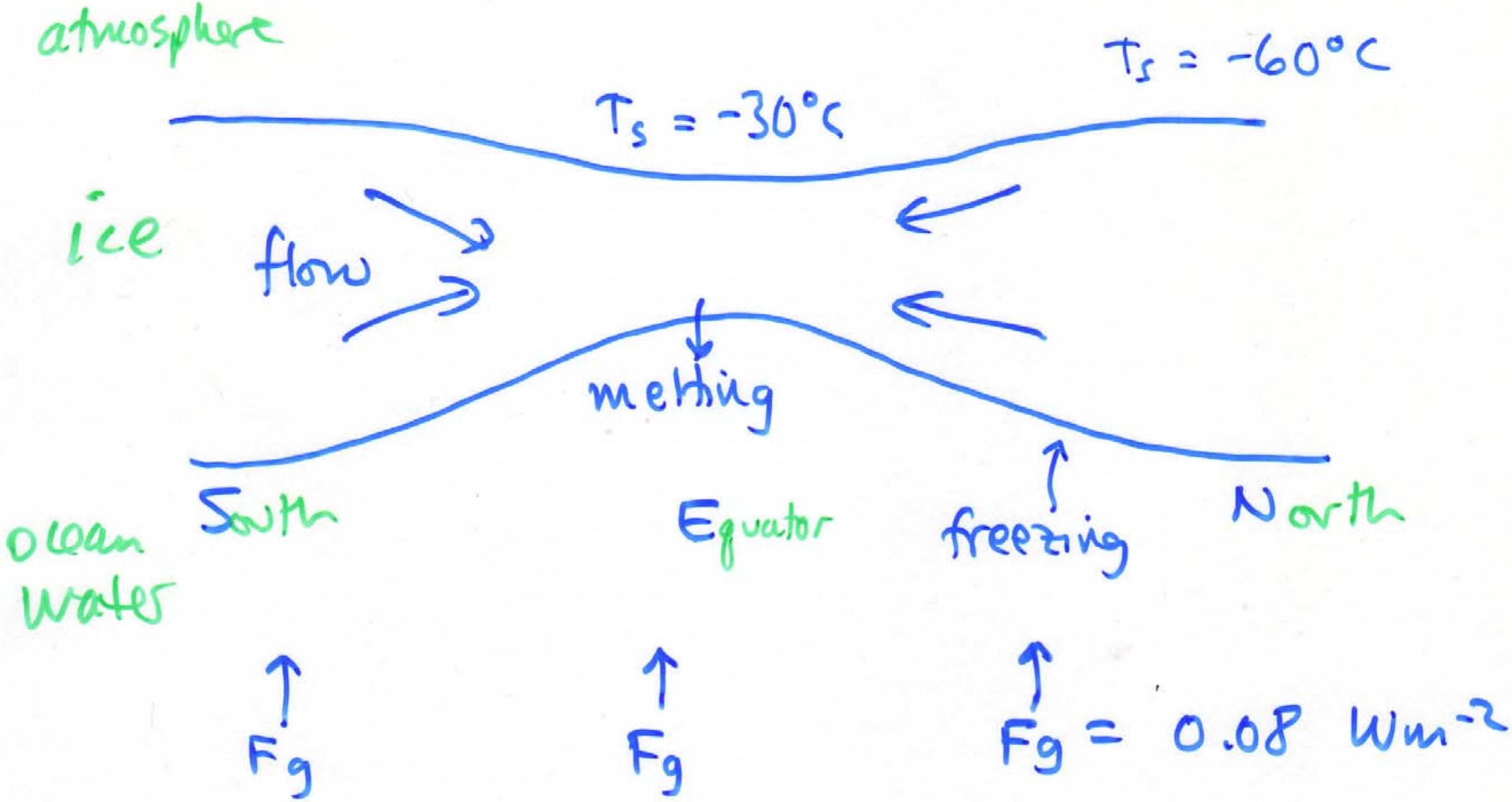
JGR-Oceans 2003

Glacial flow of floating marine ice in "Snowball Earth"

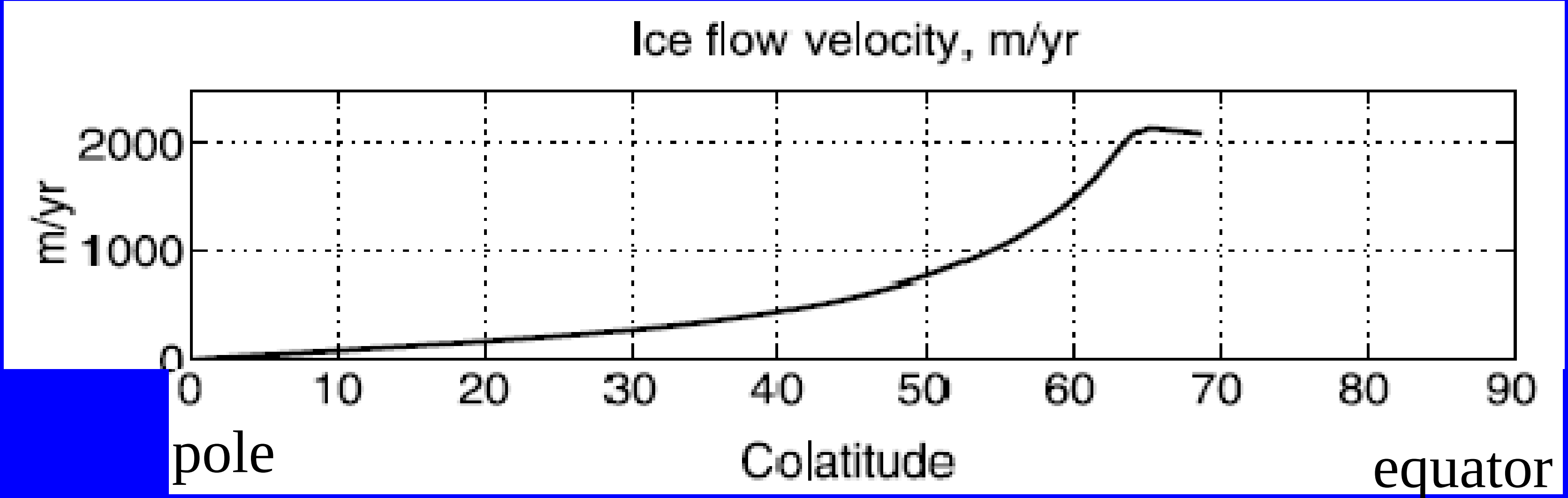
Jason C. Goodman and Raymond T. Pierrehumbert
Department of Geosciences, University of Chicago, Chicago, Illinois, USA

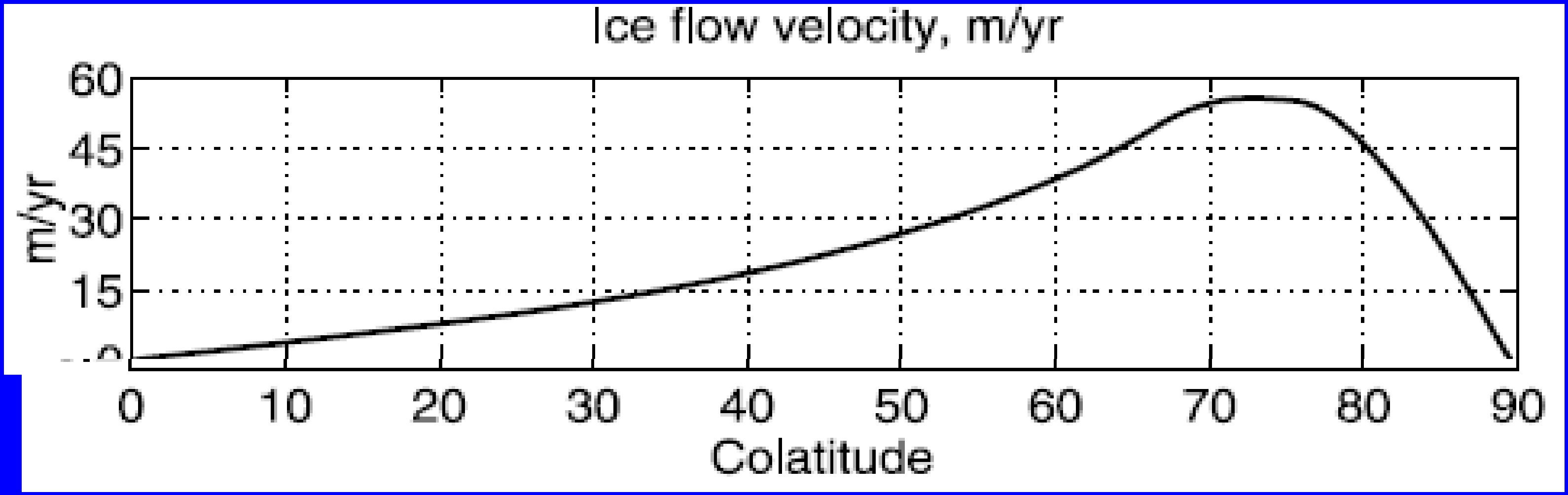
Received 9 May 2002; revised 10 February 2003; accepted 23 July 2003; published 2 October 2003.

[1] Simulations of frigid Neoproterozoic climates have not considered the tendency of thick layers of floating marine ice to deform and spread laterally. We have constructed a simple model of the production and flow of marine ice on a planetary scale, and determined ice thickness and flow in two situations: when the ocean is globally ice-covered ("hard snowball") and when the tropical waters remain open ("soft snowball"). In both cases, ice flow strongly affects the distribution of marine ice. Flowing ice probably carries enough latent heat and freshwater to significantly affect the transition into a Snowball Earth climate. We speculate that flowing marine ice, rather than continental ice sheets, may be the erosive agent that created some Neoproterozoic glacial deposits. *INDEX TERMS:* 9619 Information Related to Geologic Time: Precambrian; 1620 Global Change: Climate dynamics (3309); 5416 Planetology: Solid Surface Planets: Glaciation; 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; *KEYWORDS:* neoproterozoic, glaciation, Snowball Earth, sea ice, climate models, paleoclimate

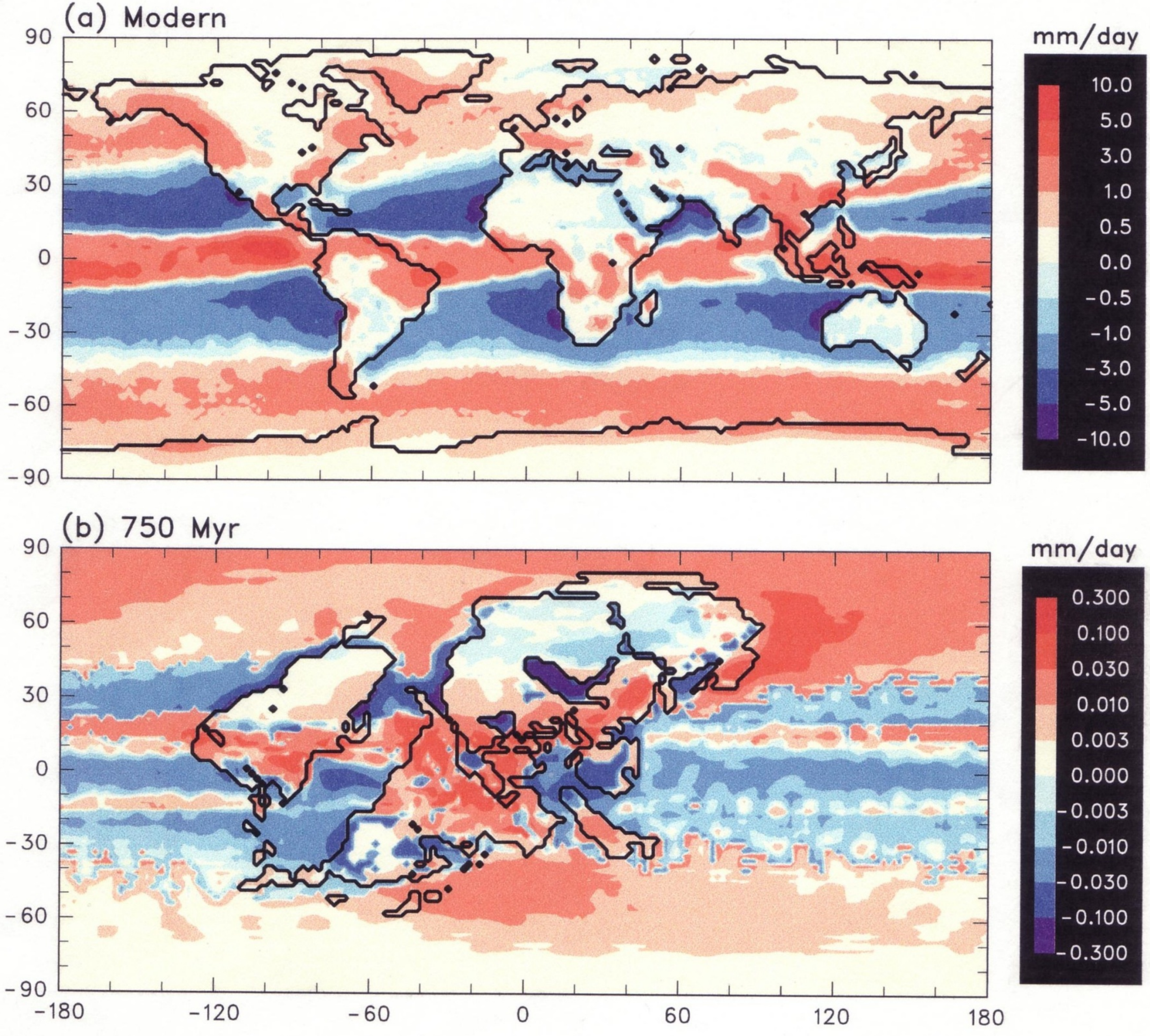


$$\Delta z = k\ \Delta T / F_g$$





Goodman & Pierrehumbert 2003



Pollard
& Kasting

GENESIS
GCM

Precipitation
minus
evaporation

Albedo of ice and snow on the ocean surface determines:

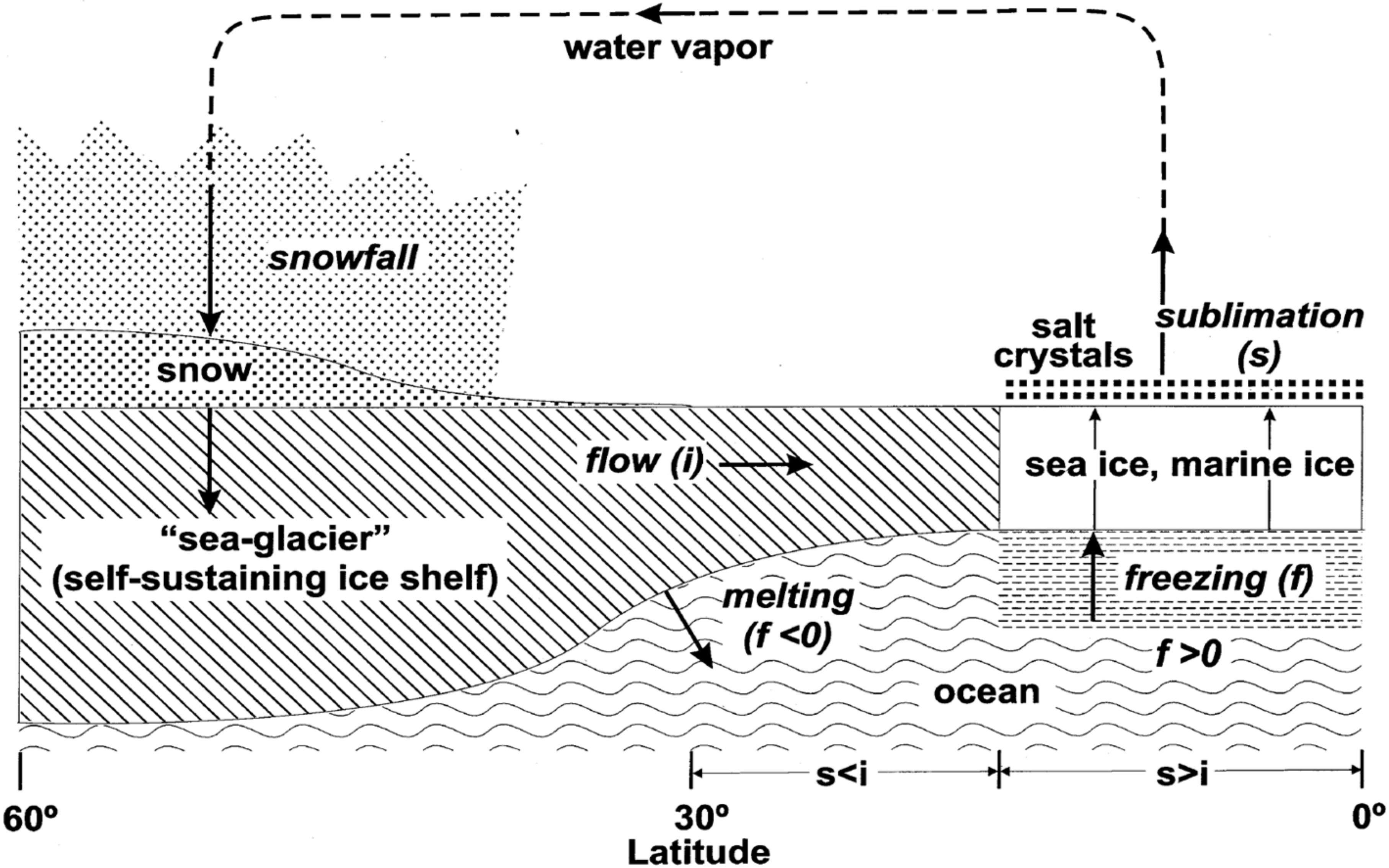
Drawdown of atmospheric CO_2 necessary to initiate snowball

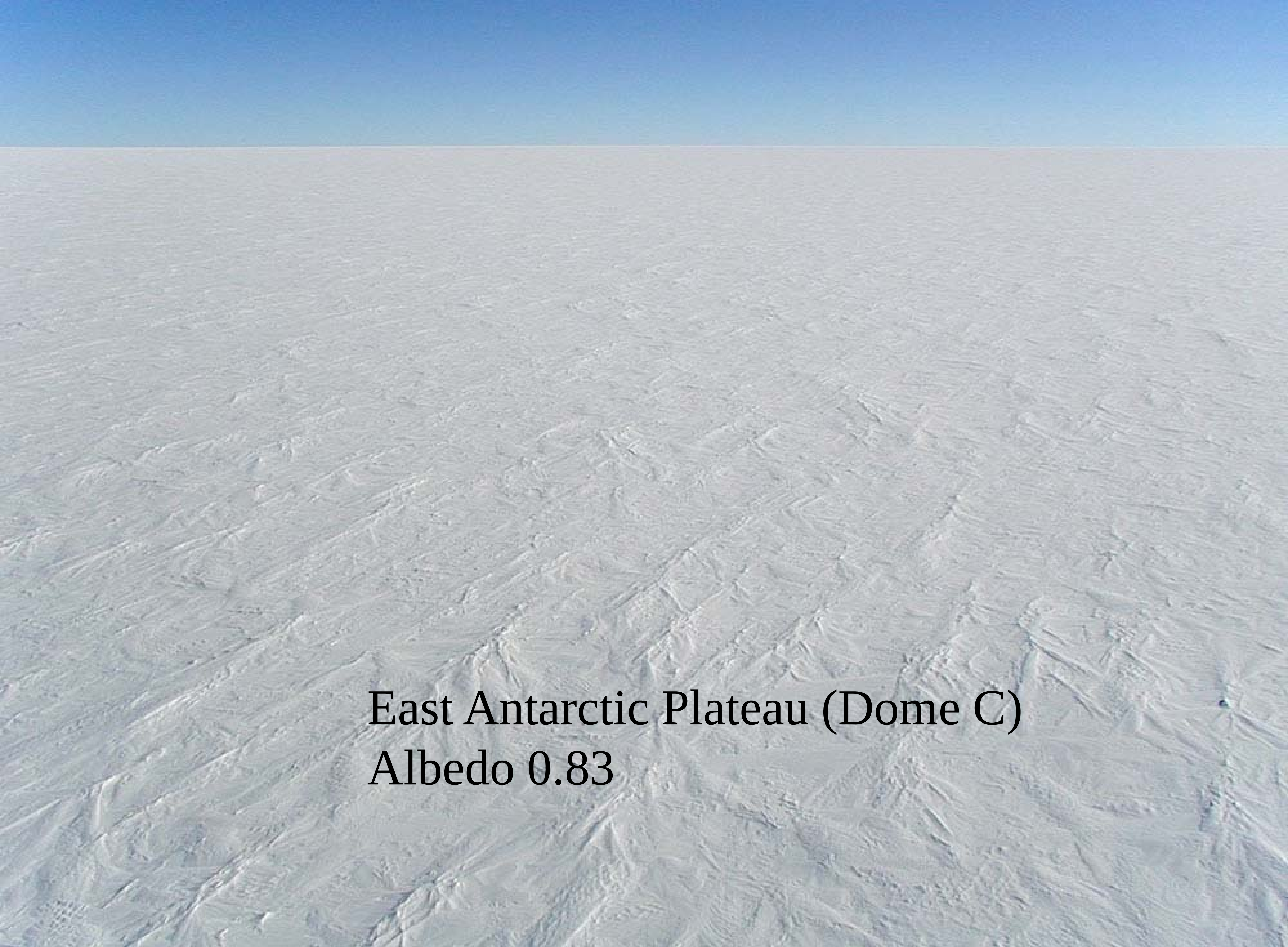
Critical latitude for ice-albedo instability

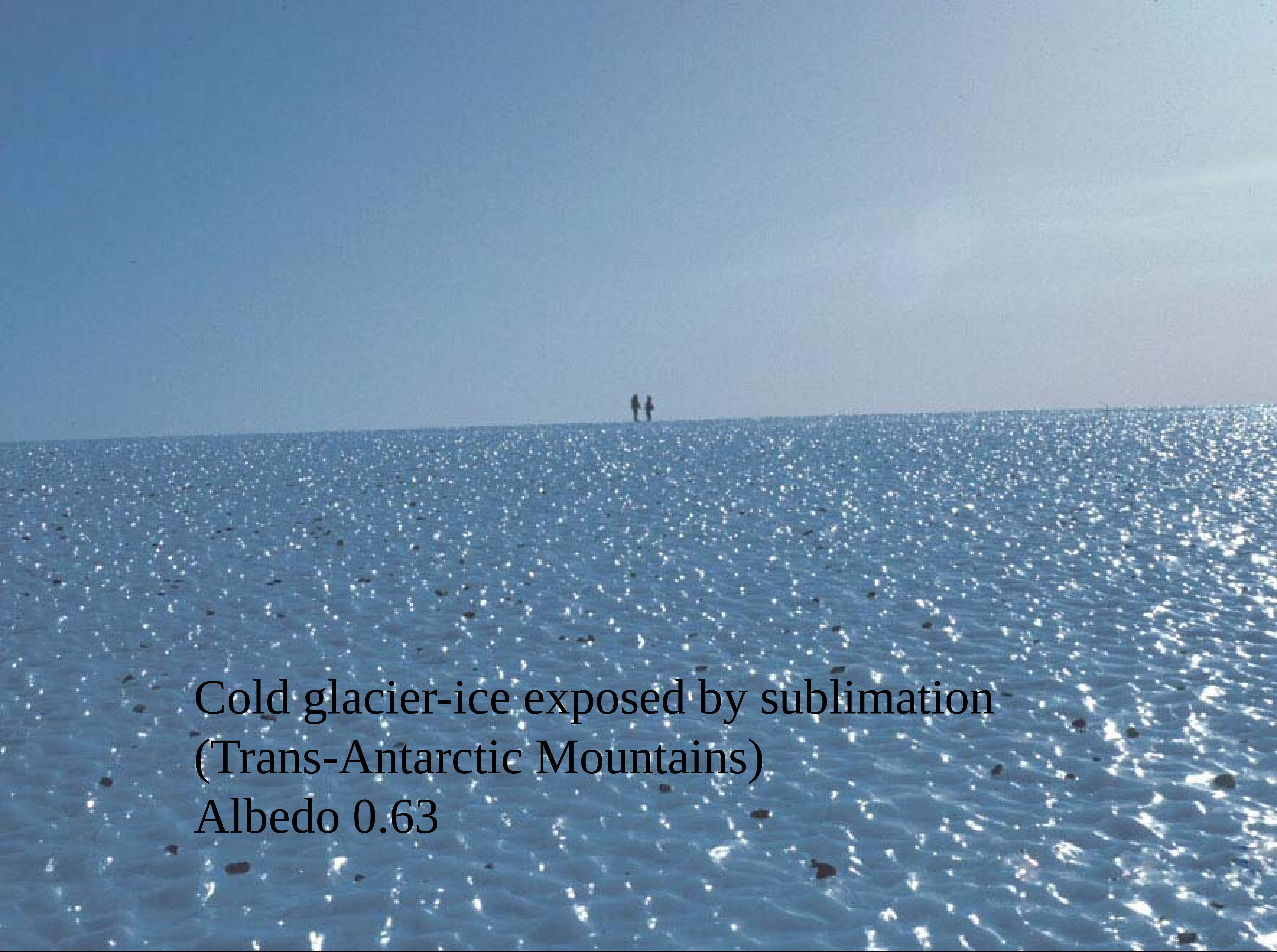
Surface temperatures of Snowball Earth

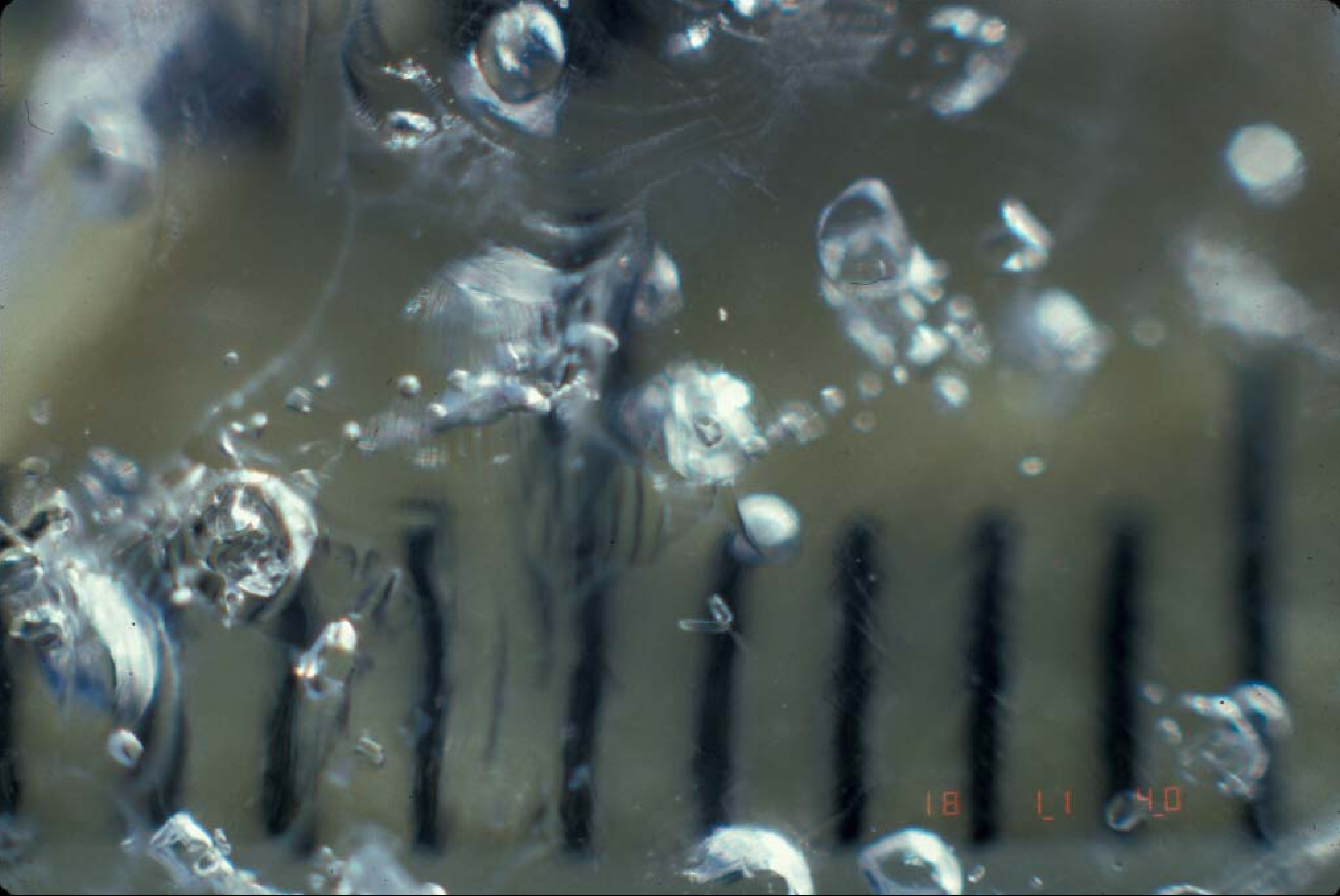
Duration of a snowball event (how much volcanic emission of CO_2 is required to warm the climate to melt the ice)

Ice thickness (limiting refugia for photosynthesis)

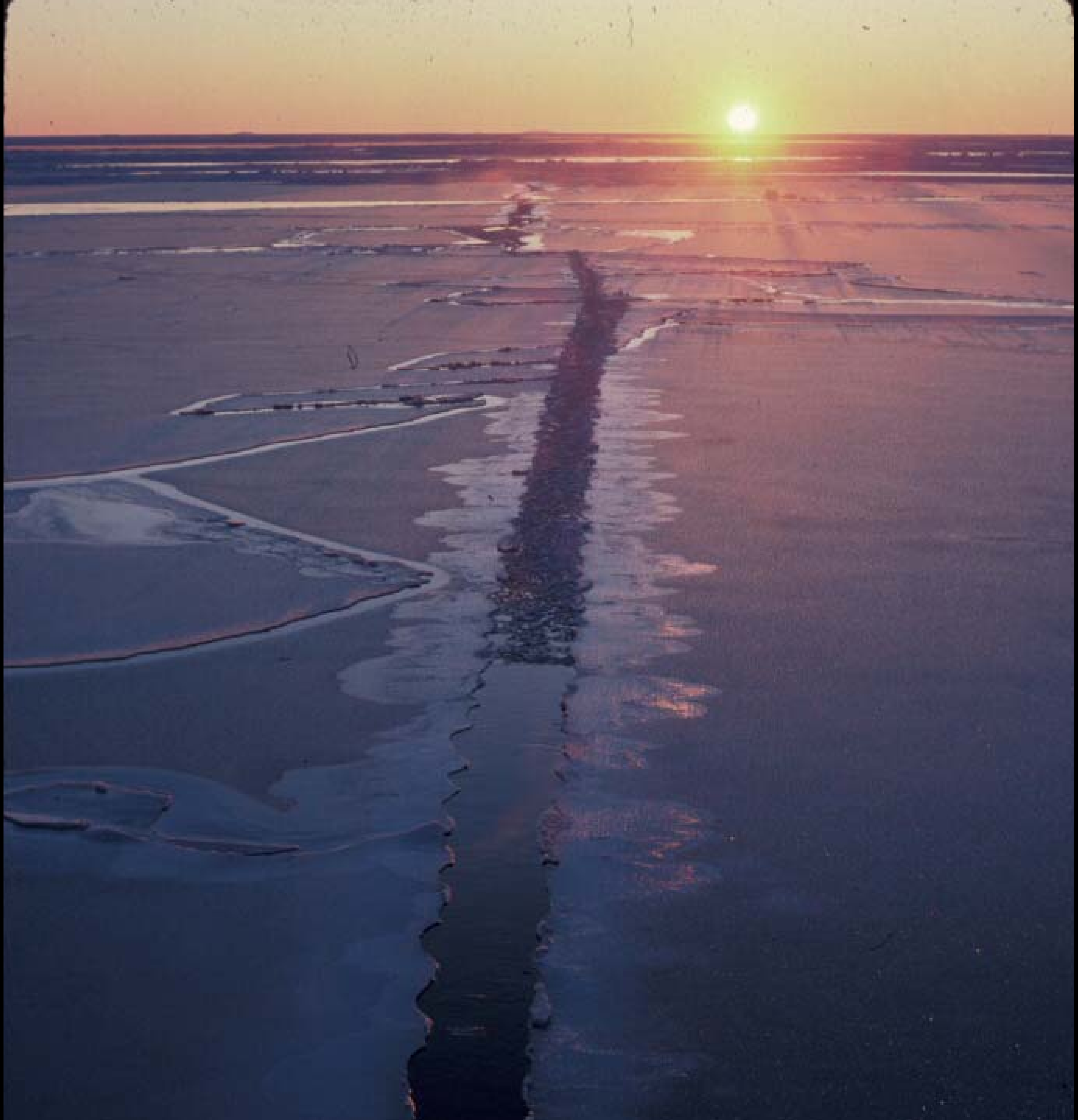

water vapor
snowfall
snow
salt crystals
sublimation (s)
flow (i)
sea ice, marine ice
"sea-glacier"
(self-sustaining ice shelf)
freezing (f)
melting (f <0)
f >0
ocean
s<i
s>i
60º
30º
Latitude
0º


East Antarctic Plateau (Dome C)
Albedo 0.83


Cold glacier-ice exposed by sublimation
(Trans-Antarctic Mountains)
Albedo 0.63



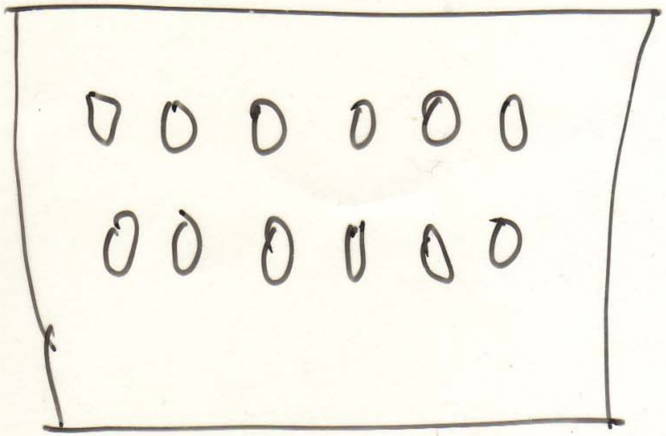
Bubbles in glacier ice surface. Tick spacing 1 mm.



Bare sea ice, 1.4 meters thick. East Antarctic coast.
Albedo 0.49 at -5 C; probably rises to 0.7 below -23 C

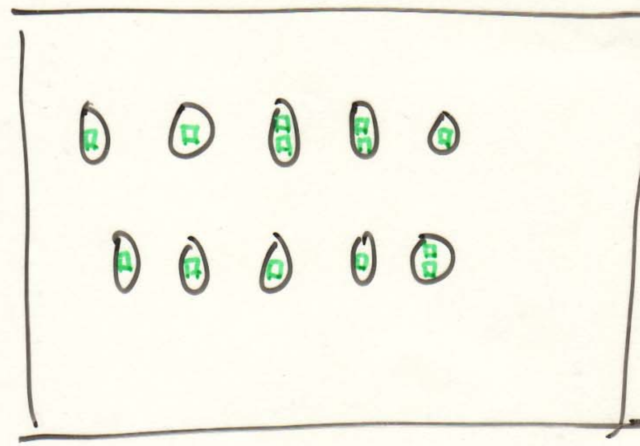
BRINE POCKETS IN SEA ICE

$T > -23°C$



albedo ~ 0.5

$T < -23°C$



salt crystals:

- $NaCl \cdot 2H_2O$ hydrohalite
- $Na_2SO_4 \cdot 10H_2O$ mirabilite

albedo ~ 0.7

(laboratory experiment by Don Perovich, 1979)

Development of salt crust

The initial catastrophic freezing of the low-latitude ocean surface would result in sea ice with salinity 4-6‰.

At a sublimation rate of 1-10 mm/yr, after 200-2000 years the top 2 meters of ice would sublimate away, leaving a salt crust of thickness 1 cm.

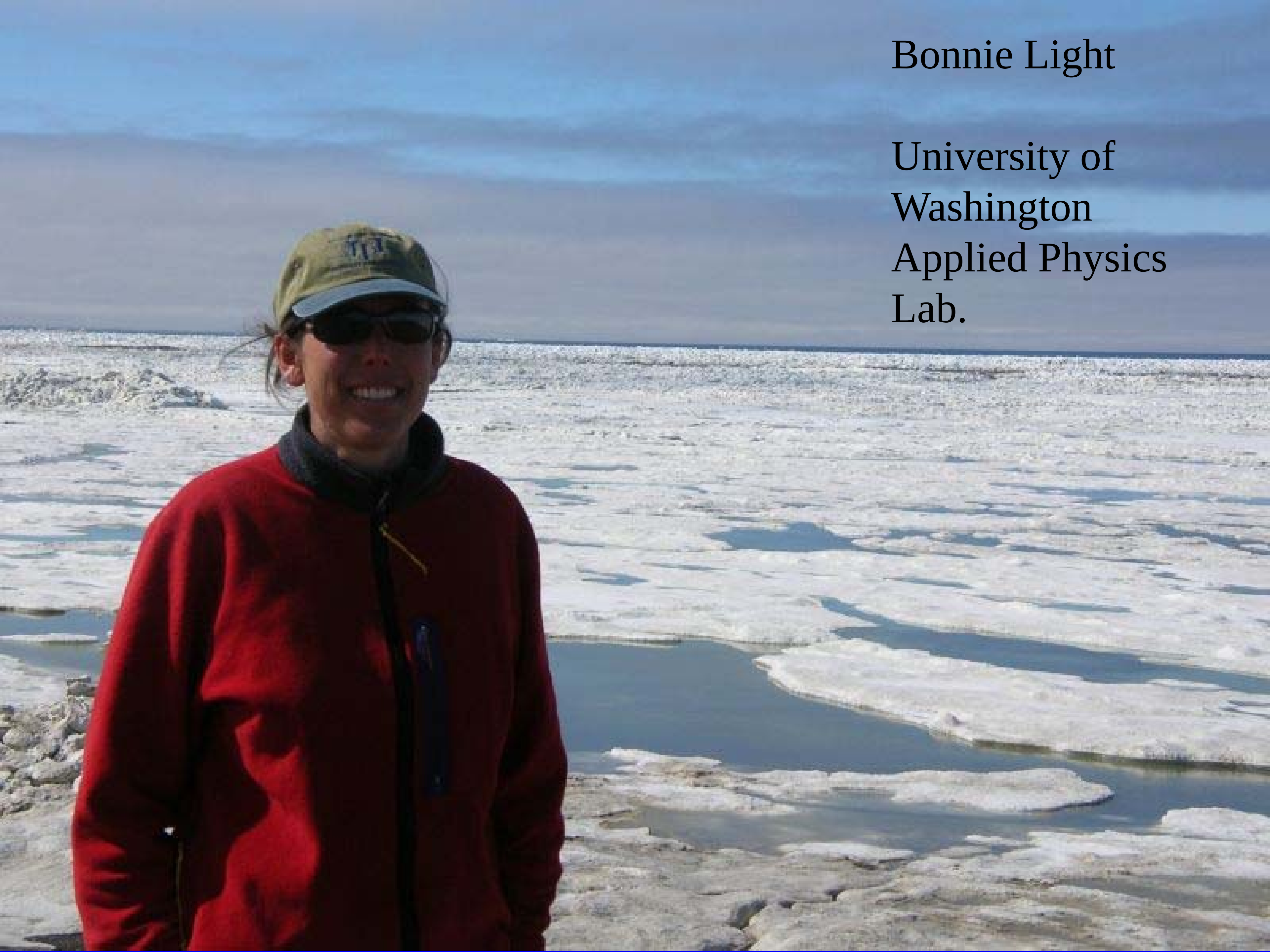
How long would the salt crust persist?

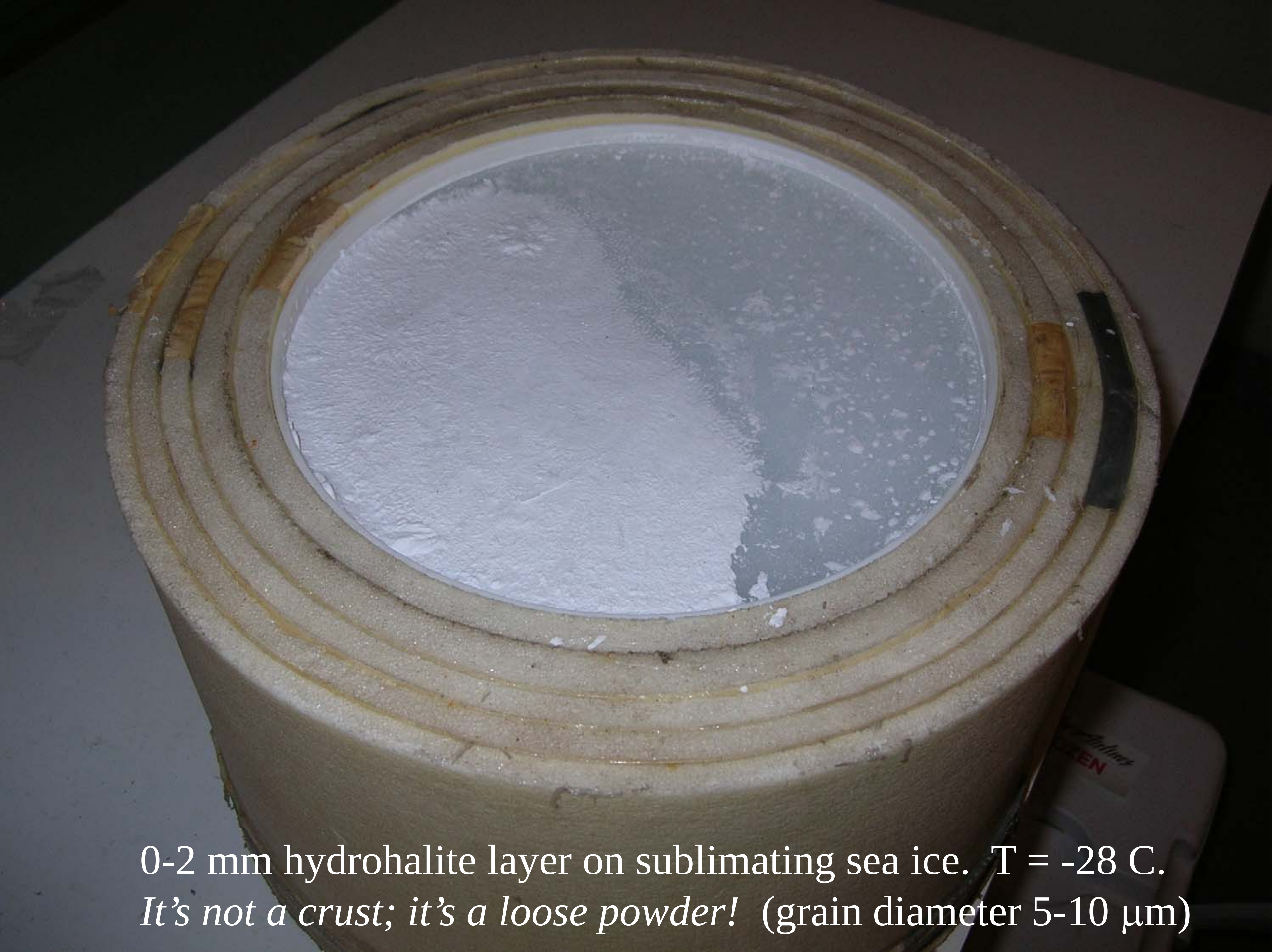
Cooling of ocean, flow of sea-glacier,
and development of salt crust
are all on time scale ~1000 yr

Halite (NaCl)

Bonneville
Salt Flats, Utah

Hydrohalite $NaCl \cdot 2H_2O$


Bonnie Light
University of Washington Applied Physics Lab.



0-2 mm hydrohalite layer on sublimating sea ice. T = -28 C.
It's not a crust; it's a loose powder! (grain diameter 5-10 μm)

Summary: Oceanic processes on Snowball Earth

Salt crust on sea ice may keep equatorial albedo high during a few hundred years after initial freezing while the ocean is cooling, until sea-glaciers advance to the equator and crush the sea ice (with its salt crust)
- but the salt may blow away!

Sea-glacier flow brings high-albedo bubbly ice to low latitude; keeps ice thick (Goodman 2006).

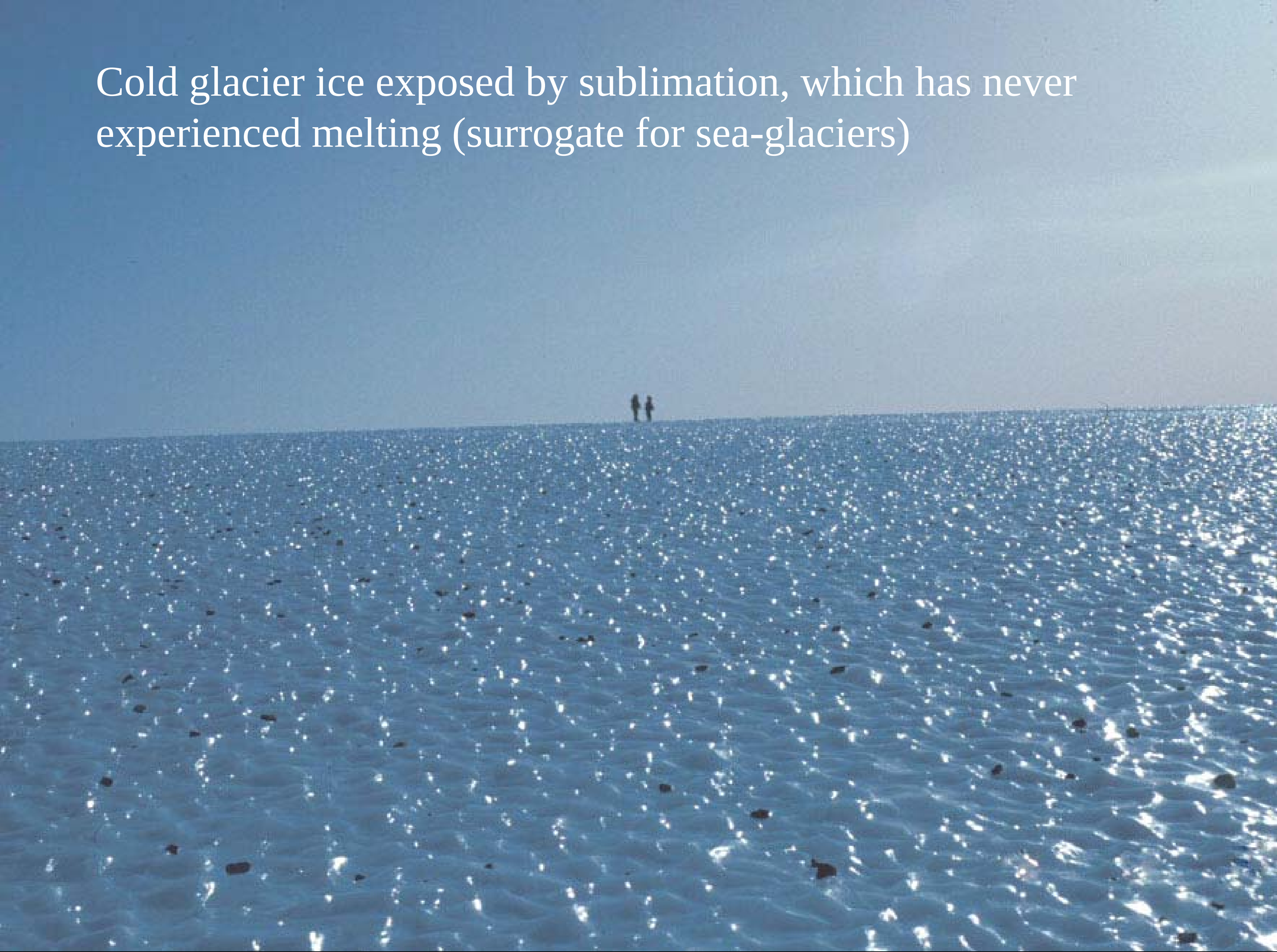
Albedo-lowering by dust and melt-puddles is probably important for termination of Snowball events

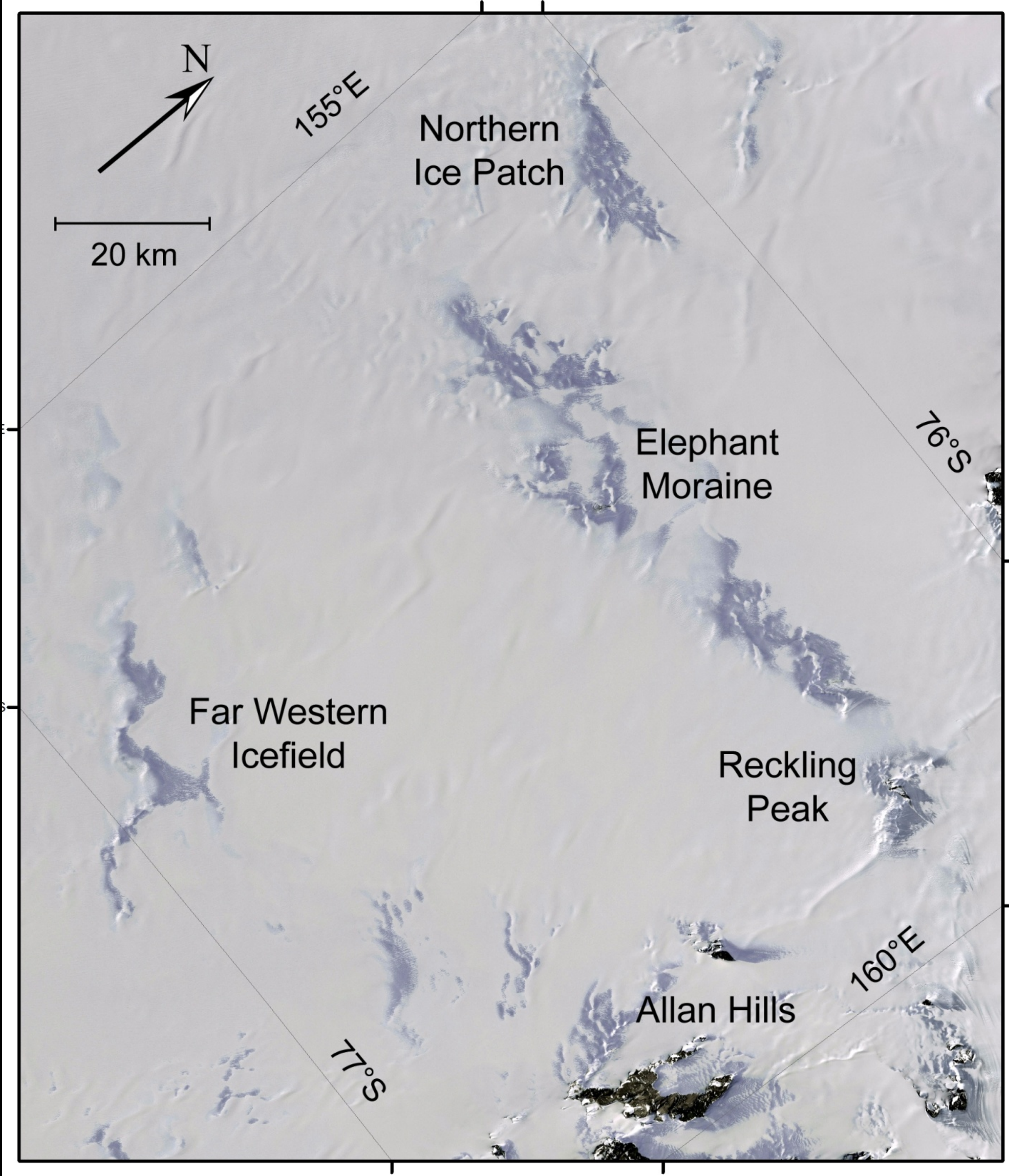
UW project: Ocean Surfaces on Snowball Earth (Funding from NSF)

Co-PIs: Bonnie Light, Ed Waddington

1. ***Laboratory work on brine, air bubbles, salt crusts***
2. ***Field measurements***
3. ***Modeling of sea-glacier flow***
4. ***Modeling of dust (albedo, and transport by sea-glaciers)***

Cold glacier ice exposed by sublimation, which has never experienced melting (surrogate for sea-glaciers)





November 2010 - February 2011

Regina Carns

Richard Brandt

Cold first-year sea ice in McMurdo Sound (ice surface temp. –34 C)

First-year sea ice covered with 3 mm of salty snow.
West of Tent Island in McMurdo Sound

Halite ($NaCl$)

Bonneville
Salt Flats, Utah

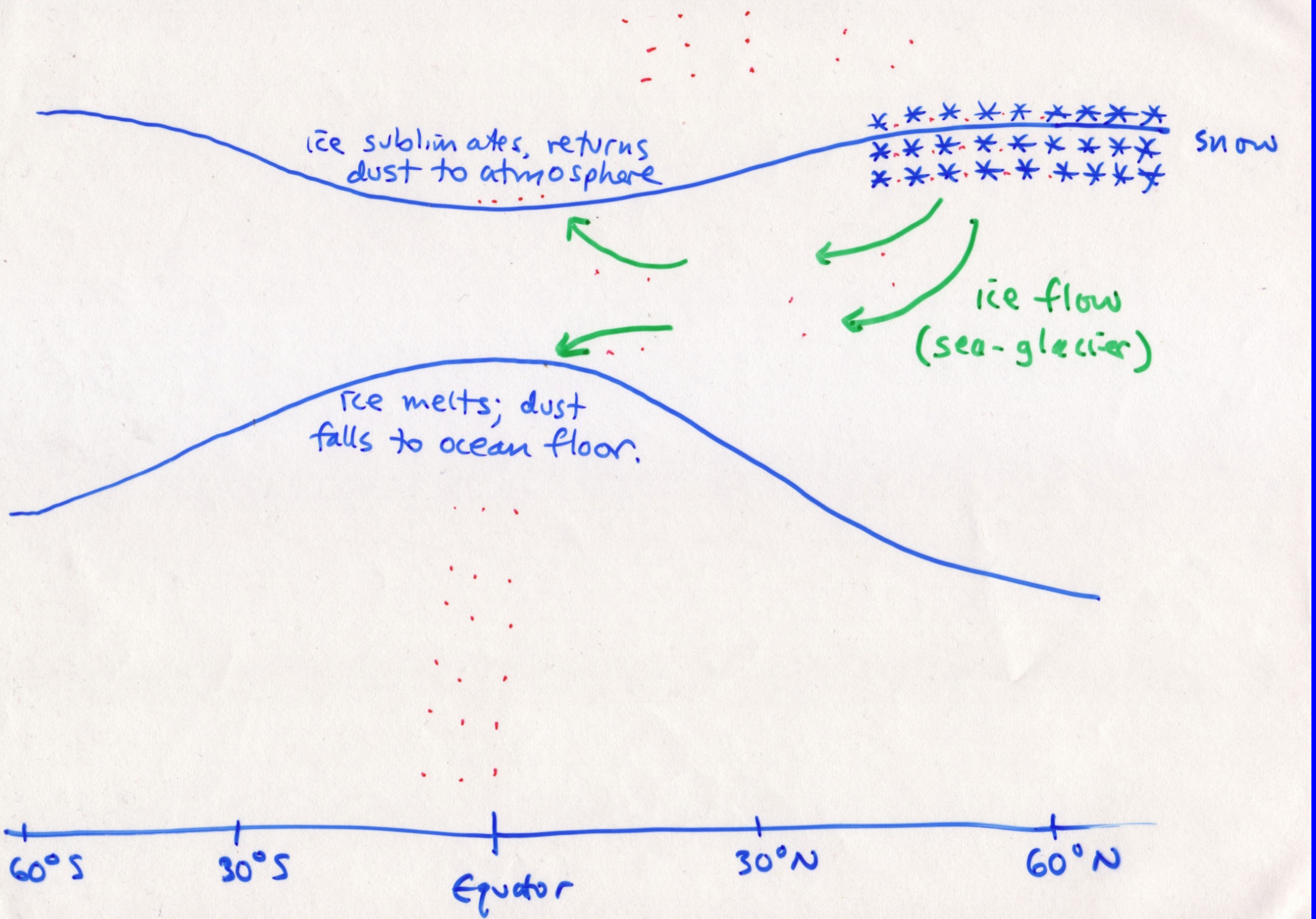
Dust

From wind-erosion of desert continents

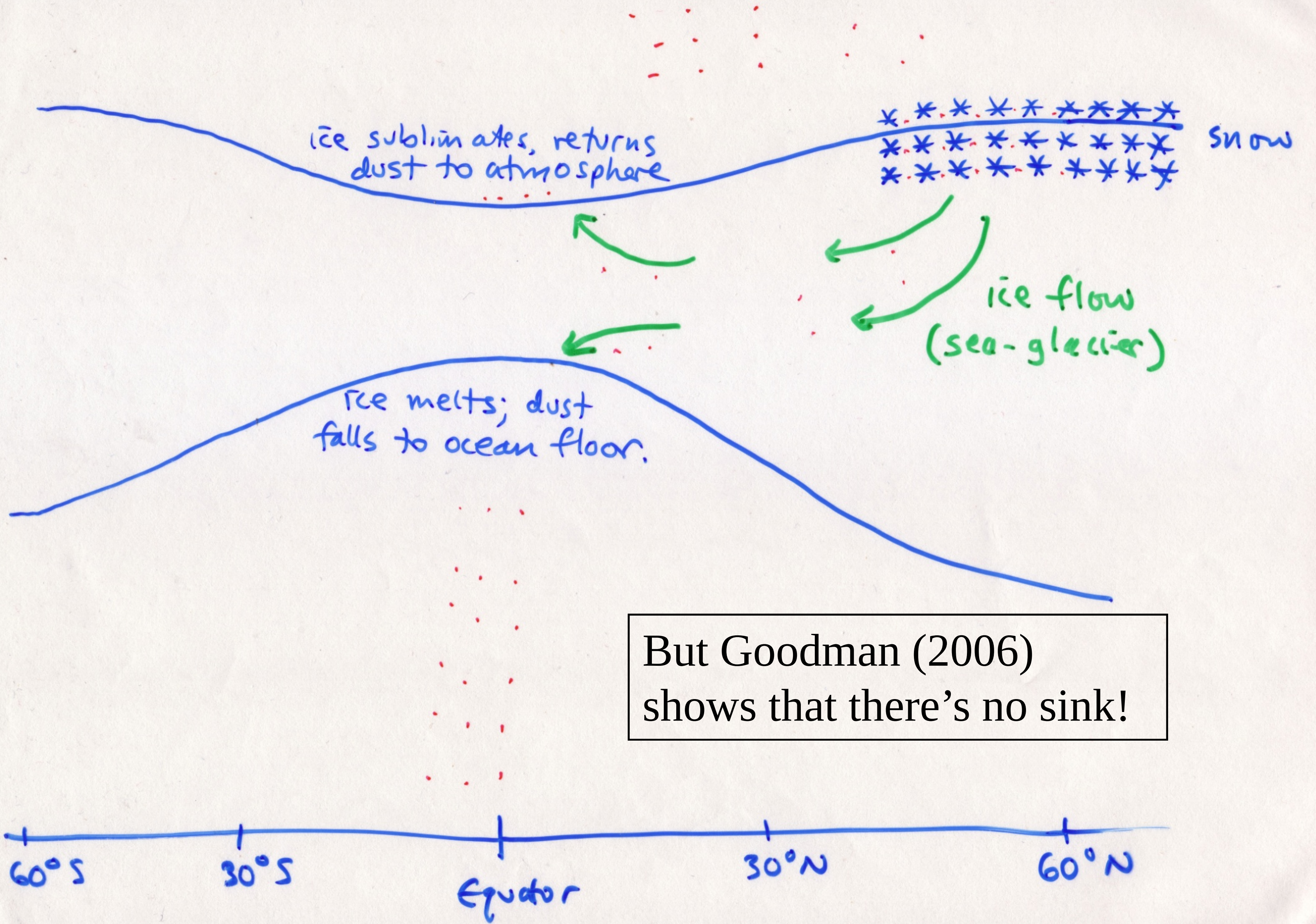
Accumulates in snow; maybe not on ice

Will assist deglaciation

Dust cycle on Snowball Earth



Dust cycle on Snowball Earth



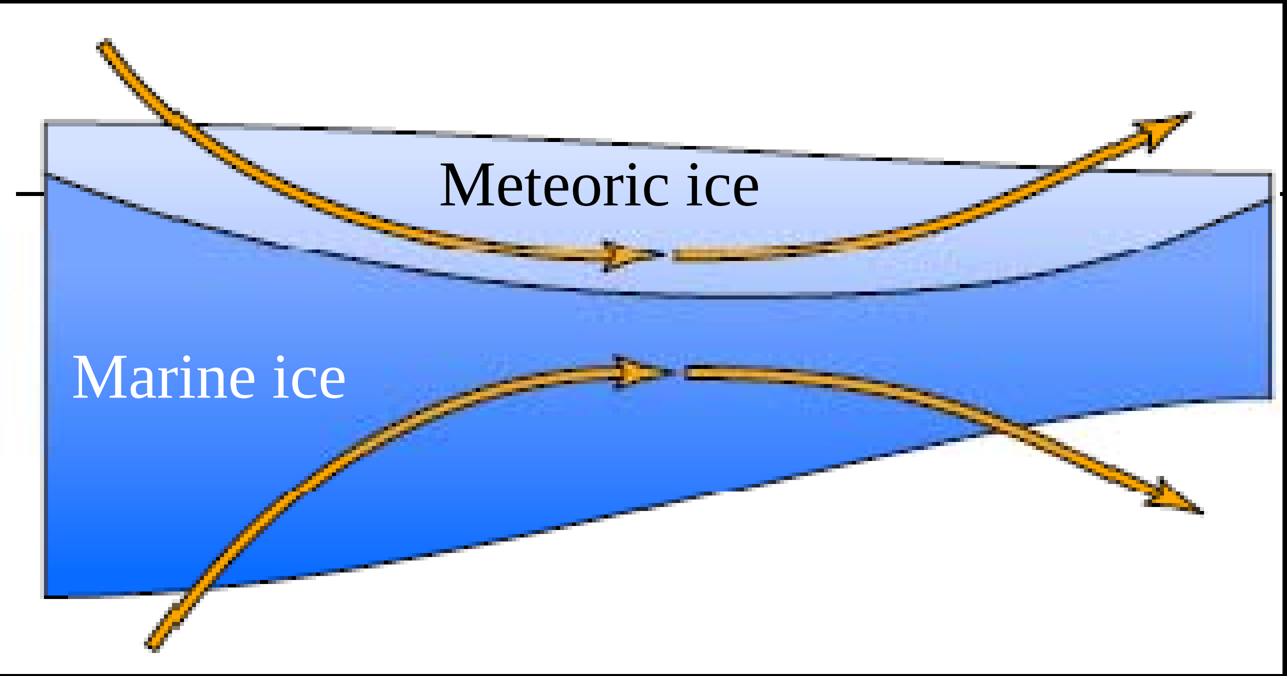
But Goodman (2006) shows that there's no sink!

GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L16701, doi:10.1029/2006GL026840, 2006

Through thick and thin: Marine and meteoric ice in a "Snowball Earth" climate

Jason C. Goodman[1]

Received 8 May 2006; revised 15 June 2006; accepted 19 June 2006; published 16 August 2006.



Meteoric ice
(from snowfall)
Maximum thickness
100 m

Dust deposition on *Ice*

To hide ice requires <0.1 mm dust (of grain radius 1 μm) if uniformly distributed. So patchiness is important.

To get 1-cm layer requires
50 kyr based on Dry-Valley erosion rate;
600 kyr if fallout as in Greenland LGM;
40 Myr if fallout as in modern Antarctica

But: ice will transport dust equatorward

Dust transport

1. Transport by wind:
   blows off ice, trapped by snow

2. Transport by sea-glaciers:
   - builds dust-moraine at equator
   - 50 kyr transit time from 60° latitude to equator.
     If 10^6 yr of dust accumulates in 1° “moraine” (0.5 N – 0.5 S), depth is 18 m at Dry-Valley erosion rates.
   - moraine suppresses sublimation

Other sources of dust to darken the ice

- volcanoes
- asteroid

Termination of a Snowball event

To assist deglaciation:

1. *Dust:*

A reduction of albedo by 1% causes a radiative forcing of 3.4 W m^{-2}, comparable to that caused by an increase of CO_2 pressure from 0.1 to 0.2 bars (4 W m^{-2})

2. *Melt-puddles in the afternoon at elevated CO_2*